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MEASUREMENT OF UNSTEADY PRESSURES IN ROTATING SYSTEMS

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16. Abstract The principles of the experimental determination of unsteady periodic pressure distributions in rotating systems are dealt with. An indirect method is discussed, and the effects of the centrifugal force and the transmission behavior of the pressure measurement circuit are outlined. The required cor- rection procedures are described and experimentally imple- mented in a test bench. Results show that the indirect method is suited to the measurement of unsteady nonharmonic pressure distributions in rotating systems.			
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Notation

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B	Magnitude
c_B	Transmission ratio of the magnitude
c_{Ph}	Transmission ratio of the phase angle
F	Surface area
f	Frequency
h	Angular sensitivity
Im	Imaginary portion
m	Mass
p	Pressure
q	Stagnation pressure
R	Gas constant
r	Radius/Cylindrical coordinate
Rea	Real portion
T	Temperature
U	Circumferential velocity
V	Free stream velocity
Z	Centrifugal force
β	Angle of sideslip
ζ	Angle
ρ	Density
ϕ	Phase angle
ψ	Cylindrical coordinate
Ω	Gyrofrequency

*Numbers in the margin indicate pagination in the foreign text.

1. Introduction

If we want to measure nonsteady pressure distributions for /127 a rotating system, such as a helicopter blade or a ship's propeller, for reasons of cost it is not always possible to provide each necessary pressure measuring point with a pressure pick-up. An alternative is to use the indirect measurement method in which a larger number of pressure borings are connected by hose lines and a switching system with a pressure sensor. As a result of using hoselines, however, the influence of centrifugal forces and the transmission behavior of the pressure lines substantially influence the measurement problem.

In a study carried out using the indirect measurement method on a rotating propeller [1, 2] it became obvious that several fundamental experiments would be necessary here to clarify the problems arising. Therefore a test stand was developed with which it was intended to investigate all of the problems involved here. This article discusses the first findings obtained with this new test stand.

2. Test Setup

The basic idea behind this test stand consisted of recording a quasi-steady spatially differentiated flow state with a rotating probe and with an extended measurement technique for non-steady processes.

The section to be picked up from the flow field as a signal for the nonsteady process can be determined using stationary measurement techniques. Comparison with the nonsteady measurement then provides information on the nonsteady measurement process used. A variation in the parameters determining the problem--state of the oncoming flow, signal shape, rpm, radius and construction of the pressure transmission line--should provide information on the accuracy and limits of the measurement method. In addition, with this test stand it is intended to investigate a few technical problems which result from the rotation of the measuring device.

Fig. 1 shows a sketch of the test stand developed on the basis of the above considerations for the 3-meter wind tunnel of the DFVLR-AVA in Göttingen. Downstream from a diaphragm (1) placed in the path of the wind tunnel stream there is a probe arm driven by a motor. To this arm is connected a total pressure probe (2) which can be moved in a radial direction. The probe is connected to a pressure transducer on the probe slide and to one in the axis of rotation.

The diaphragm which deforms the tunnel flow consists of two faces each with four sectors of a circle. The position of the sectors with respect to one another can be varied by rotating one of the faces. Setting the variable sector at ψ_v establishes a signal shape which repeats itself four times on the circumference, assuming a uniform oncoming flow.

3. Rotating Total Pressure Probe

The total pressure was selected as the variable to be measured, since a total pressure probe shows a relatively simple response behavior with different directions of oncoming flow as a result of rotation. In Fig. 2 is plotted the angular sensitivity $h(\beta)$ measured for the probe used. In the velocity range studied (10 to 40 meters per second) there turned out to be no dependency on the Reynolds number for $0 < \beta < 90^\circ$. Thus the stagnation pressure q for a sliding probe turns out to be

$$q = \frac{p_{ges}(\beta) - p_\infty}{h(\beta)} \quad (1)$$

If the probe is rotated in the flow field in the y - z plane, it follows that the effective oncoming flow velocity is:

$$V_{eff} = (v^2 + u^2)^{1/2} \quad (2)$$

with

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$$U = r \cdot \Omega = r \cdot 2\pi f$$

(3)

with the angle of oncoming flow β :

$$\beta = \arctan \frac{U}{V} .$$

(4)

In the same way as with the sliding probe, the effective stagnation pressure q_{eff} turns out to be:

$$q_{\text{eff}} = \frac{p_{\text{ges}}(\beta) - p_{\infty}}{h(\beta)} .$$

(5)

Thus with Eq. (2) the stagnation pressure becomes:

$$q = \frac{p_{\text{ges}}(\beta) - p_{\infty}}{h(\beta)} - q_{\text{rot}}$$

(6)

with

$$q_{\text{rot}} = \frac{\rho}{2} U^2 = 2\rho r^2 \pi^2 f^2 .$$

(7)

4. Influence of Centrifugal Force

Apart from the possible effect of centrifugal force on parts of the measurement apparatus, the centrifugal force affects the gas volume in the line between the pressure measurement point and the pressure transducer if this is not arranged at the same distance r from the axis of rotation.

The centrifugal force acts on a volume component $F \cdot dr$ at a distance r :

$$Z = \frac{m \cdot U^2}{r} = \frac{\rho \cdot F dr \cdot (2\pi r f)^2}{r} = 4\pi^2 F f^2 \rho \cdot r dr .$$

(8)

With the equation of state this becomes:

$$Z = \frac{4\pi^2 F}{RT} f^2 p r dr \quad . \quad (9)$$

In the equilibrium state it must be true that:

$$Z = dpF \quad . \quad (10)$$

It follows from Eqs. (9) and (10) that:

$$\frac{dp}{p} = \frac{4\pi^2}{RT} f^2 r dr \quad (11)$$

with the solution

$$p_1 = p_2 e^{-\frac{2\pi^2}{RT} f^2 (r_2^2 - r_1^2)} \quad . \quad (12)$$

Thus the change in pressure due to centrifugal force is known. In this test setup measurements are made with pressure element II (see Fig. 1) in the axis of rotation. With $r_1 = 0$ and $r_2 = r$, from Eq. (12) the pressure at the point of the probe p_2 is calculated from the measured pressure p_1 as follows:

$$p_2 = p_1 e^{\frac{2\pi^2}{RT} f^2 r^2} \quad . \quad (13)$$

With the series expansion

$$e^x = 1 + \frac{x}{1} + \frac{x^2}{1 \cdot 2} + \dots \quad (14)$$

for $x \ll 1$, taking into account the first two expansion terms, we obtain the following from Eq. (13):

$$p_2 = p_1 \left(1 + \frac{2\pi^2}{RT} f^2 r^2 \right) \quad . \quad (15)$$

Since $p_1 = p$, we obtain

$$p_2 = p_1 + \frac{p}{2RT} 4\pi^2 r^2 U^2 = p_1 + \frac{\rho}{2} U^2 \quad (16)$$

$$p_2 = p_1 + q_{\text{rot}}$$

Thus for the case $r_1 = 0$, $x \ll 1$, we have found a simple equation for correcting a measured pressure affected by centrifugal force.

The test results plotted in Fig. 2, which were measured with the rotating probe in uniform oncoming flow, are corrected according to Eq. (13) with respect to the centrifugal force effect. The good agreement between the results of the rotating probe determined with different test parameters and the statically measured angular sensitivity show both the validity of the influence derived above for the centrifugal force and the applicability of the statically determined sensitivity to a rotating system.

5. Determination of Periodic, Nonharmonic Events

As discussed in detail in [1], periodic, but nonharmonic, events can be measured with a harmonic analyzer (HA) developed by J. Wagener. With this device the portion of a measurement signal changing over time is picked up as a signal composed of six harmonic oscillations. When using the indirect pressure measurement method, it is possible with the harmonic analyzer to take into consideration the transmission behavior for the frequencies of the individual harmonic portions. If f_i is the frequency of the i th harmonic oscillation with

$$f_i = i \cdot f_0 ; \quad i = 1, \dots, n \quad (17)$$

with the basic frequency f_0 , the transmission behavior of the pressure line with respect to the magnitude $(c_B)_i$ and the phase relationship $(c_{Ph})_i$ must be determined for f_i . From the real

portions Rea_i measured with the HA and the imaginary portions Im_i , we can determine the i th portion of the oscillation process with

$$B_i = \frac{(\text{Rea}_i^2 + \text{Im}_i^2)^{1/2}}{(c_B)_i} \quad (18)$$

and

$$\varphi_i = \arctan(\text{Im}_i / \text{Rea}_i) - (c_{Ph})_i \quad (19)$$

as

$$p_i(\xi) = B_i \cdot \sin(i \cdot \xi + \varphi_i) \quad (20)$$

From the sum of the harmonic portions and the mean pressure value over time $\bar{p}$, we can determine the change in pressure over time as

$$p(\xi) = \bar{p} + \sum_{i=1}^n p_i(\xi) \quad (21)$$

with n = number of harmonic portions taken into account. Fig. 3 shows the individual portions and the composite dynamic pressure signal

$$p_{\text{dyn}} = p(\xi) - \bar{p} \quad (22)$$

These were determined with the HA for $\psi_v = 62.5^\circ$. The period of oscillation $\xi = 2\pi$ corresponds to the rotation of the probe arm of $\psi = 90^\circ$, since, because of the arrangement of the diaphragm, it is true that

$$\xi = 4\psi \quad (23)$$

6. Results

With the relationships presented in section 3, 4 and 5 we can now evaluate a pressure measurement which was measured with pressure sensor II of the test stand described in section 2. (For technical reasons, it has not been possible so far to make any measurements with pressure sensor I).

Taking into consideration Eqs. (21) and (16), the stagnation pressure from Eq. (6) turns out to be:

$$q(\xi) = \frac{\bar{p} + \sum_{i=1}^6 p_i(\xi) + q_{\text{rot}}(U) - p}{h(\beta)} - q_{\text{rot}}(U) \quad (24)$$

With the simplifications $\Delta p_{\text{dyn}}(\xi) = p_{\text{ges}}(\xi) - p_{\infty}$ and $\Delta p = p - p_{\infty}$

$\bar{\Delta p} = \bar{p} - p_{\infty}$, we can write the following equation for the measured change in total pressure with respect to the pressure of the undisturbed oncoming flow:

$$\Delta p_{\text{dyn}}(\xi) = \frac{\bar{\Delta p} + \sum_{i=1}^6 p_i(\xi) + q_{\text{rot}}(U) - \Delta p}{h(\beta)} - q_{\text{rot}}(U) + \Delta p \quad (25)$$

This equation contains the physical variables actually measured in a differential pressure measurement.

Fig. 4 shows a comparison between a statically measured pressure distribution with the test result of the harmonic analyzer at $f_0 = 14$ Hz evaluated according to Eq. (25). Both the signal shape and the absolute magnitudes of the measured pressures showed good agreement. Thus, it is shown that by taking into account the transmission behavior and the effects of centrifugal force, using the indirect measuring method leads to reliable results.

7. Summary

In the experimental determination of nonsteady periodic pressure distributions in rotating systems using the indirect measuring method, the influence of centrifugal force and the transmission behavior of the pressure measuring lines play a decisive role. The necessary correction method was derived and tested experimentally on a test stand developed for this purpose. The results show that the indirect measurement method is suitable for determining nonsteady, nonharmonic pressure distributions for rotating systems.

8. References

1. Kienappel, k., H. Triebstein and J. Wagener, Measurement of Unsteady Pressure Distribution and Forces on a Propellor in a Ship's Wake, DFVLR-AVA Report 253 - 76 C 04 (1976).
2. Kienappel, K., Repetitive Measurements of the Nonsteady Pressure Distribution of a Propellor in a Ship's Wake, DFVLR-AVA Report 253 - 76 J 09 (1976).

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Fig. 1a. Test stand, rotating pressure measurement system.

- Key:
- | | |
|--------------------------|-------------------------|
| 1. Diaphragm | 6. Cover |
| 2. Total pressure sensor | 7. Pressure element II |
| 3. Sensor slide | 8. Mechanical slip ring |
| 4. Pressure element I | 9. Hg. slip ring |
| 5. Spindle | 10. Motor |
| | 11. Counterweight |

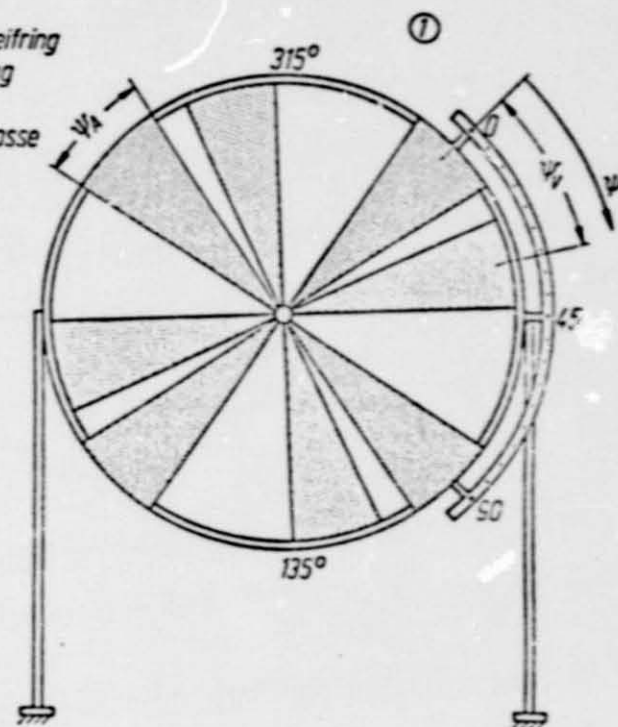
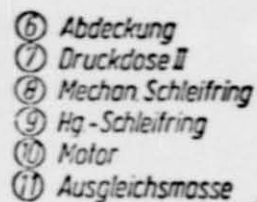


Fig. 1b. Diaphragm geomet

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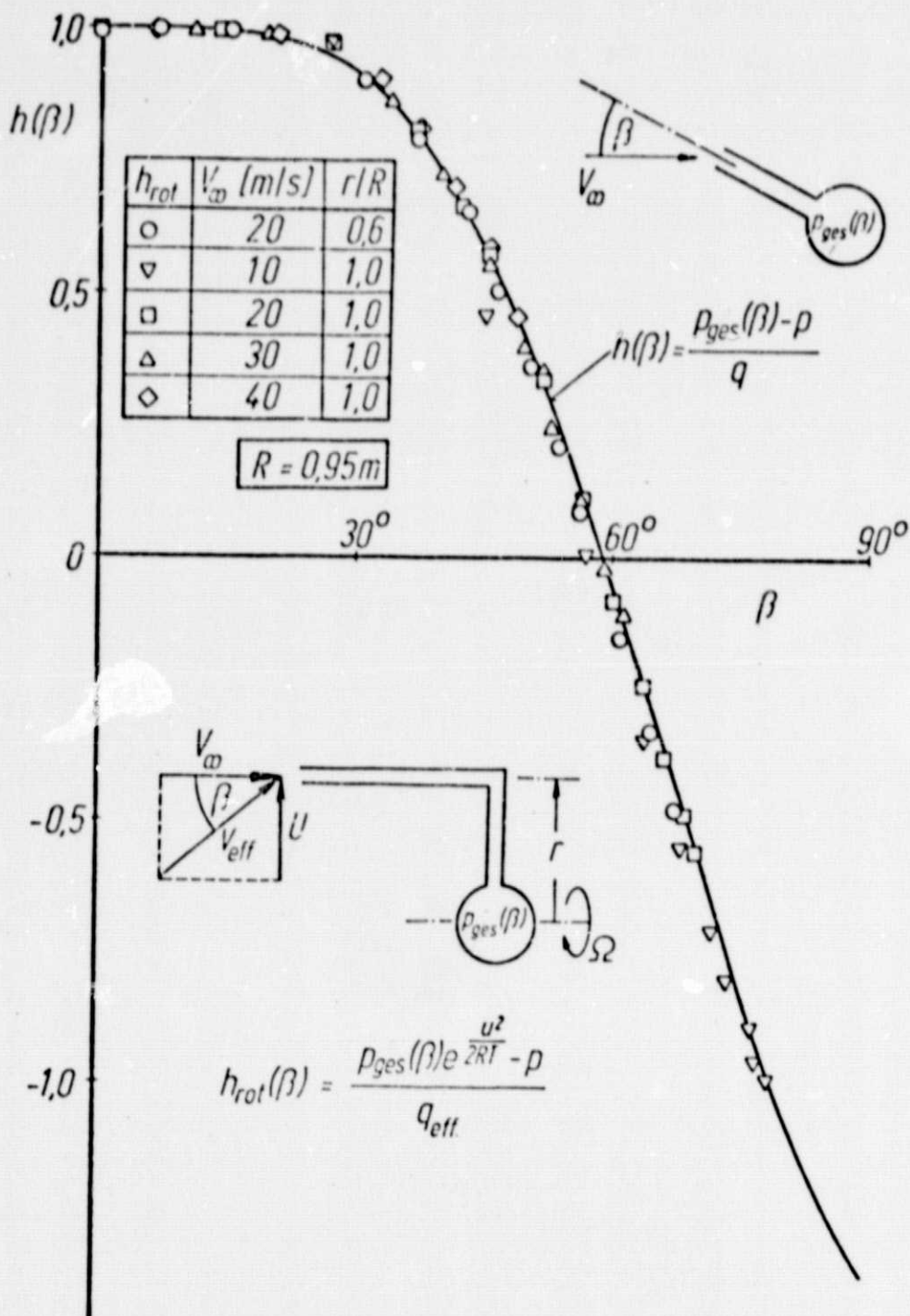


Fig. 2. Angular sensitivity of the total pressure probe in the stationary and rotating system.

Key: A. Total

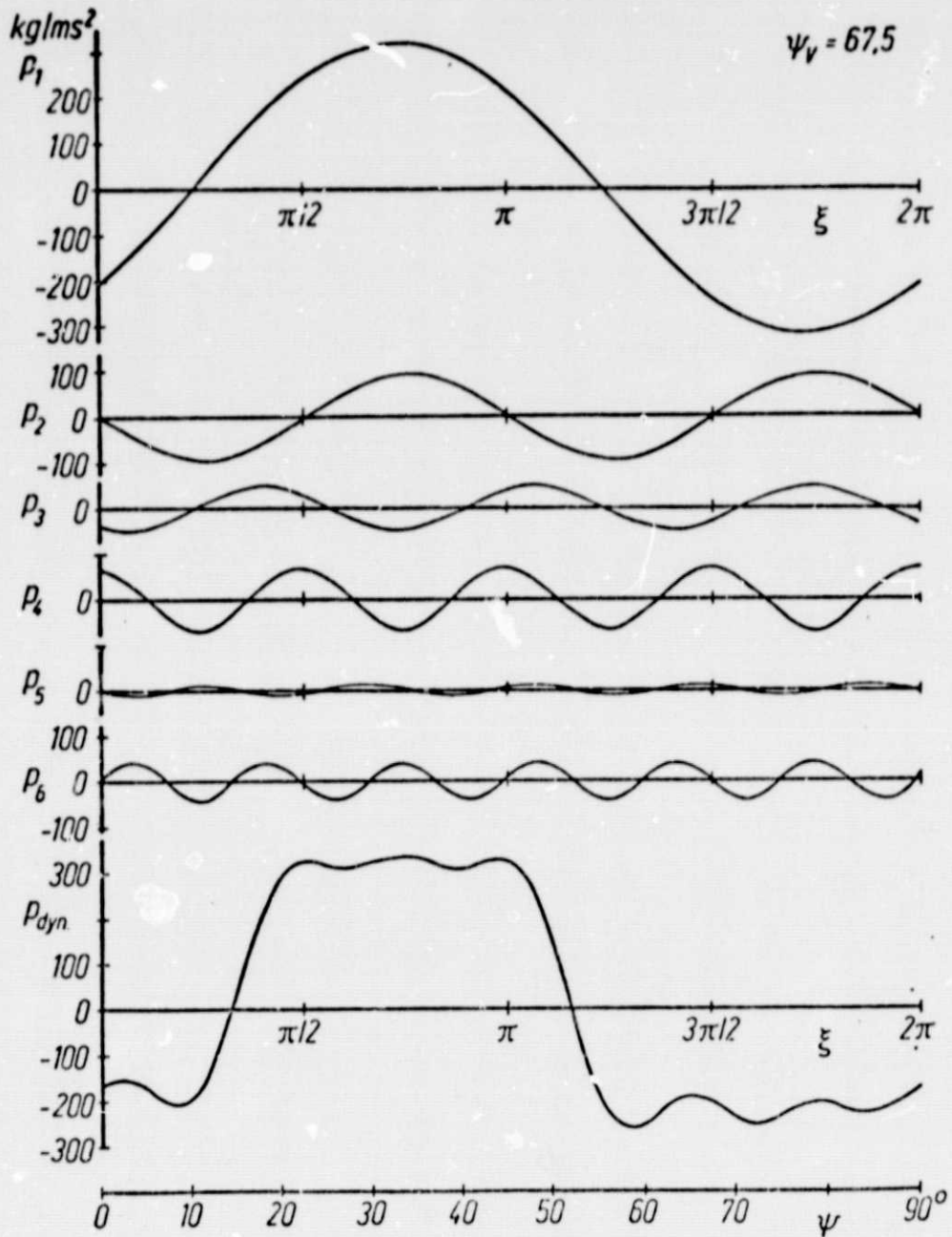


Fig. 3. Composite dynamic signal of six harmonic components.

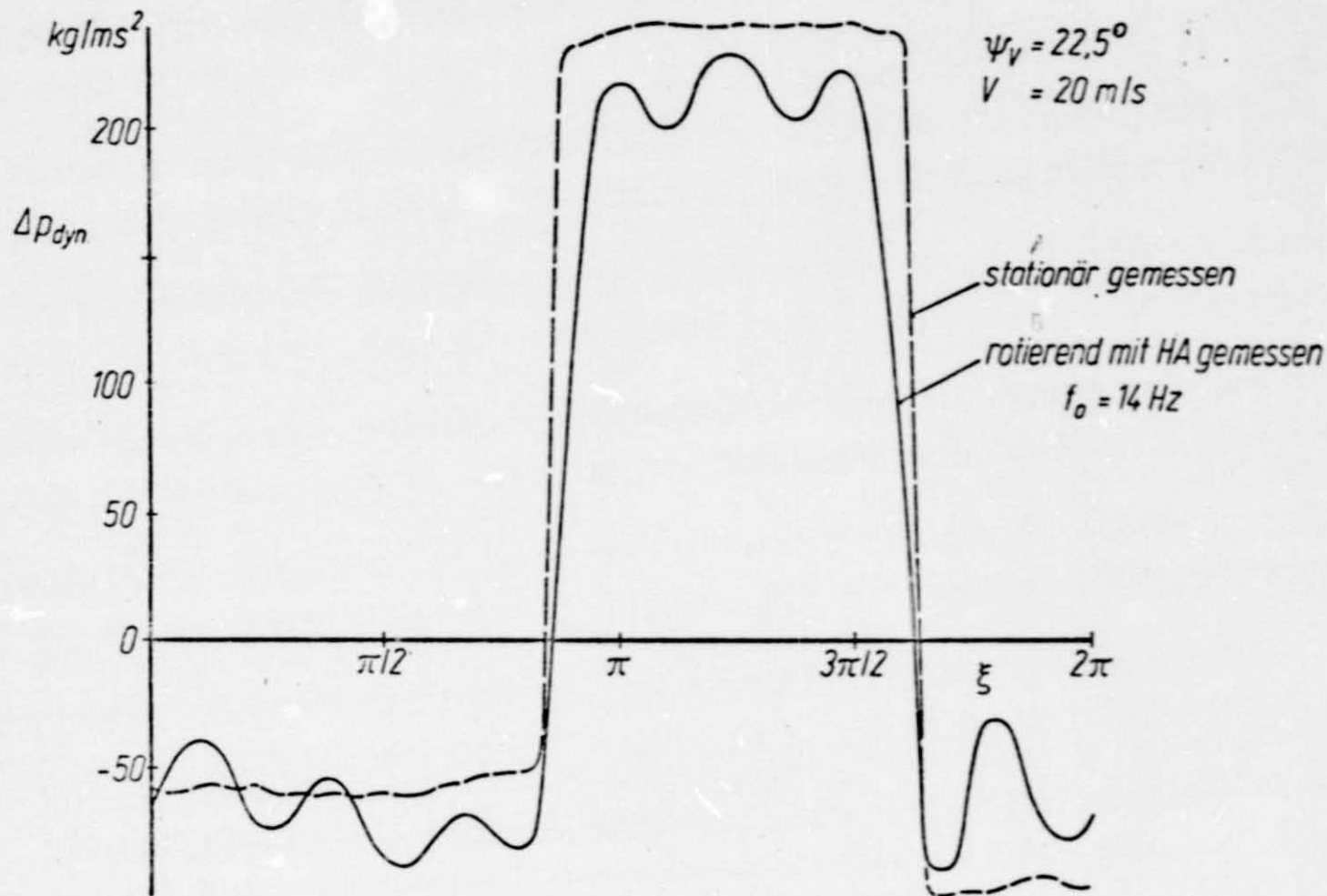


Fig. 4. Comparison between pressure signals measured in a stationary and rotating system.

Key: A. Measured in stationary system
B. Measured in rotating system with harmonic analyzer